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ASTRONOMICAL PHOTOGRAPHY FROM THE STRATOSPHERE

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FROM THE SMITHSONIAN REPORT FOR 1963, PAGES 323-329
(WITH 2 PLATES)

GPO PRICE \$ _____
CFSTI PRICE(S) \$ _____
Hard copy (HC) _____
Microfiche (MF) _____

ff 653 July 85



(PUBLICATION 4573)

SMITHSONIAN INSTITUTION

WASHINGTON : 1964

N67 13727
(ACCESSION NUMBER)
(THRU) 1
(PAGES) 11
(CODE) 30
(CATEGORY)
(NBSA CR OR TMX OR AD NUMBER)
CR-80742

FACILITY FORM 602

Astronomical Photography from the Stratosphere¹

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[With 2 plates]

THROUGHOUT the centuries astronomers have labored under one enormous handicap that has set harsh limits to all their observational work. Between celestial objects which are the subject of the astronomer's research and his telescope lies the earth's atmosphere, a murky restless layer which forever garbles our only source of information on the universe around our earth. This handicap imposed by the earth's atmosphere has made itself felt most strongly in three broad areas: First, no ultraviolet light with wavelengths shorter than 3,000 angstroms can penetrate the earth's atmosphere at all; this loss of the ultraviolet prohibits us from studying the bulk of the light emitted from the hottest and most energetic stars and prevents us from making accurate measurements regarding many of the astronomically most important chemical elements which have their main absorption lines in this spectral region. Second, large blocks of the infrared spectrum are completely blocked out by the earth's atmosphere and thus we have been unable to study the cooler stars in detail and to measure the absorption bands of many of the key chemical compounds. Third, even the ordinary visible light, though not absorbed by the earth's atmosphere—or at least absorbed only to a minor degree—does not reach our telescopes ungarbled; the turbulence of the atmosphere bends the light rays from the stars slightly and thus prevents us from getting as sharp pictures of the celestial bodies as our instruments otherwise would permit. Even at the best mountain observatories on those rare occasions when the atmosphere above behaved relatively quiescently only a very small number of astronomical photographs have been obtained which show details as small as half a second of arc; this angle corresponds to half a mile on the moon,

¹ The 28th annual James Arthur lecture on the sun, given under the auspices of the Smithsonian Institution on May 8, 1962.

200 miles on the sun, and several light years in the nearest stellar systems such as the spiral Andromeda Nebula. Clearly, even our best photographs have been coarse indeed.

The astronomical profession had adjusted itself through the centuries to labor under this all-prevailing handicap. Then, about a decade ago new technical tools appeared which promised to remove this handicap for good: Rockets began to lift above the earth's atmosphere small telescopes with which for a few short minutes the ultra-violet light of the sun and the stars could be studied; balloons carried astronomical cameras above 95 percent of the atmosphere and brought down for the first time sharper photographs of astronomical objects; now satellites are being developed which will carry major astronomical instruments far above the earth's atmosphere and may permit effective research there for long time intervals.

It is hard to describe the force of the impact that this development has had on astronomy as a science and on astronomers as persons. Even now astronomers are far from having reached a balanced adjustment to the new circumstances; we are still swaying back and forth between elation and bewilderment. Nevertheless, I think it is by now obvious that the new tools of rockets, balloons, and satellites open up an immense area for astronomical research, though it would be clearly a grave mistake to consider these new tools actually as replacements for the old ground-based instruments and techniques, rather than as decisive and stimulating additions.

If, from here on, I concentrate entirely on one specific astronomical balloon project—Project Stratoscope—my sole reason is that I am very closely acquainted with this activity. Project Stratoscope is only a minute facet in the entire program of off-the-ground astronomical and geophysical research. However small in the overall research picture, for those of us involved it has been and continues to be an absorbing and immensely exciting activity.

Project Stratoscope arose from a specific scientific problem. The tremendous energies produced by hydrogen burning in the interior of the sun are carried out to the surface by enormous convective movements of the gases in the outer layers of the sun. These convective movements can actually be seen on the surface of the sun in the form of the granulation, the fine mottled structure covering the entire solar surface at all times. It became clear that to understand the detailed mechanism by which this convective motion of the gases transports the heat energies outward is an unavoidable prerequisite to following the evolutionary changes of any star such as the sun. On the other hand, it became desperately clear that, though the detailed observational study of the solar granulation would help much toward this understanding, such detailed observations on the ground were made essentially impossible because of the image deterioration caused by the

earth's atmosphere. For this reason we decided to study the possibility of sending a telescope up on a balloon with the specific purpose of obtaining high-definition photographs of sample areas on the solar surface. When these studies indicated that such an undertaking appeared technically feasible we decided to go ahead with it—elated and filled with awe at the same time.

The instrument built for this specific research, Stratoscope I, had to fulfill two central conditions: First, it had to contain optics capable of producing a highly enlarged image of the solar surface on the photographic emulsion; for this purpose a parabolic mirror 12 inches in diameter was used as the primary optical element followed by an enlarging lens which produced an image of part of the solar surface with a scale equivalent to a telescope with a 200-foot focal length. Second, this telescope had to be pointed toward the sun by electrical motors steered by electronic devices so steadily that the telescope would not turn by more than about a fifth of a second of arc in the required exposure time of about two-thousandths of a second of time, an extremely exacting condition on pointing steadiness indeed.

We flew this instrument for the first time in the summer of 1957. After a preliminary test flight with a dummy telescope to determine whether the balloons and launching techniques then employed were capable of safely carrying a delicate optical instrument into the stratosphere and whether the return of the instrument by parachute was practicable, two flights were carried out with Stratoscope I, itself. These two flights brought down 16,000 photographs of parts of the solar surface. Nearly all of these photographs were of poor quality because of a number of instrumental inadequacies disclosed by subsequent analysis. Among this vast number of photographs, however, we found about half a dozen superb ones, which for the first time showed the detailed structure of the convective elements in the solar granulation well. We returned home from that first flight season jubilant—and still filled with a sense of awe.

The next 2 years we were strenuously occupied by measuring and analyzing the fundamental characteristics of the solar convection shown on our best photographs and deducing from these data tentative conclusions regarding convective energy transport in stars relevant for the theory of stellar evolution. At the same time we concentrated hard to eliminate the instrumental faults shown up in the first flights of Stratoscope I. Also, we made one major modification of the instrument which increased greatly the effectiveness of this telescope as a research tool. This was the addition of a radio-command link from a ground station to the unmanned balloon telescope by which the focus of the telescope could be regulated and by which the telescope could be pointed at will to any portion of the solar disk. To make this command link effective we also added a small television link

which permitted us to see in the ground station exactly the picture being photographed at the telescope.

In the summer of 1959 we were ready for another sequence of flights. The character of these flights was entirely different from those in 1957 in one decisive respect. In 1957 after launch the entire balloon and telescope system operated completely automatically, according to its built-in program of operations without any possibility of human influence during the flight. In 1959, when the balloon had reached its stable altitude of 80,000 feet in the stratosphere, a small group of engineers and astronomers in the ground station took over the actual operation of the telescope through the newly added command and television links. It is hard to describe the excitement we felt as for the first time we saw on the television screen the picture of a piece of the solar surface and as this picture moved about over the surface of the sun in perfect accordance to the radio commands we gave. We thus could select during the flight particularly favorable areas for our research, such as areas on the solar disk far removed from any apparent disturbance like sun spots or prominences. Or, in contrast, we could move to an area occupied by an active sunspot group to study the effects of the magnetic fields in the sunspots on the convective gas motions.

If human control during the flight so greatly increased the effectiveness of this research undertaking, one might ask whether it would not have been better if one of us had gone up in a sealed capsule with the telescope. I believe that such a manned flight would not have been a good choice; the effort required to safeguard the life of the person going up would seem far larger than the effort required in developing the necessary radio links to permit human control from the ground. Furthermore, the person in his capsule, attached to the same suspension from the balloon to which the telescope itself must be attached, would have had to avoid any motion whatsoever to preserve perfect quietness for the telescope pointing. This strong conviction that unmanned balloon flights are preferable for this type of astronomical experiment in no way implies the opinion that manned high-altitude balloon flights have not been of decisive value. Indeed, I believe that without the vital and energetic enthusiasm for manned stratospheric balloon flights balloon technology would never have developed to the state that permitted us to lift Stratoscope I into the stratosphere. I strongly suspect that much the same situation will hold in the satellite field. It seems entirely plausible that most of the research results from the space program will come from unmanned space vehicles. It appears equally true, however, that the natural human urge for manned flight into space is the essential driving force behind the technological developments necessary for any space flights.

But back to Project Stratoscope. After a series of four flights we

returned home in the fall of 1959 with a couple of hundred high-definition solar photographs. These contained not only detailed pictures of the granulation, both in undisturbed and in highly disturbed magnetic regions, but also full-time sequences of both types of areas. Thus it became possible in the subsequent analysis to determine not only the distribution of sizes of convective elements in the solar atmosphere but also the average period of time a typical convective element exists. These observational data have greatly strengthened our theoretical picture of convective heat transport in stars. As a matter of fact we at Princeton as well as astronomers at other institutions are continuing with the theoretical developments helped and stimulated by these measurements.

The sun is by no means the only celestial object of which higher definition photographs are needed for the solution of fundamental astronomical research problems. The sky is full of objects the essential details of which are blurred on photographs taken with telescopes on the ground. There is Venus with its cloud cover, the structure of which has hardly been glimpsed. There is the great Orion gas nebula in which we are sure from indirect evidence stars are now being formed; but whether this giant gas mass is smooth or knotty or filamentary we still cannot judge from our present photographs though we need to know before we can securely develop a theory of the origin of stars. There is the Andromeda spiral nebula with its incredibly dense stellar nucleus defying photographic resolution. Many items can be added to this list, all referring to objects that are typical examples of the celestial phenomena filling the universe around us. Of all these it is only for the sun that the modest aperture of 12 inches of Stratoscope I would suffice to obtain substantially sharper photographs than those already available from the ground. The other objects would require a telescope with at least a 36-inch aperture. After the first successful flights of Stratoscope I it was tempting to start studying the feasibility of a larger balloon-borne telescope and in due course we did begin the design and construction of such an instrument—now called Stratoscope II.

The requirements regarding optical perfection and pointing accuracy are, of course, much higher for the larger Stratoscope II than they were for Stratoscope I. For example, the pointing accuracy will have to be better than a thirtieth of a second of arc over exposure times as long as 1 hour to make Stratoscope II fully effective. The requirements on optical perfection and on guidance are much less stringent if Stratoscope II initially is used not for high-definition photography but for spectrophotometric investigations in the infrared. The latter presents another effective astronomical use of a balloon-borne telescope since the few percent of the atmosphere above 80,000 feet are practically transparent in the infrared (though they are still entirely

opaque in the ultraviolet). We decided therefore to take a more cautious approach and first use Stratoscope II for a study of the infrared spectrum of Mars during its opposition early in 1963. Stratoscope II was ready for infrared spectrophotometric research in February of this year and was launched on its first flight on the evening of March 1. The events of that night could not have been more exciting for any of us involved.

The late afternoon launching went entirely smoothly; the specially designed balloon, capable of flying a gross load of 13,000 pounds, lifted the 3-ton telescope off the ground by a newly developed static launching method with accelerations not exceeding 0.2 g. In the meantime the ground station had been set up about 200 miles downwind along the predicted flight path for the night. This ground station provided a link between the engineers and scientists in it and the telescope high above it that was far more extensive and versatile than that used in Stratoscope I. In total more than 70 different commands could be transmitted to the instrument and a similar number of data relative to the telescope could be read in the ground station via a telemetry channel. Even a full-scale television channel was available to make possible the acquisition of any object in the sky. Through these radio links Stratoscope II is perhaps at the moment the most versatile scientific robot operated from a far distance by man.

However, as might not be so unexpected, this robot misbehaved in a variety of ways during his first flight. A series of inadequacies and direct failures occurred throughout most of the night. The versatility of the command system made it possible, however, to analyze the difficulties sufficiently well to make possible their correction prior to the next flight, and even to overcome to a certain extent their negative consequences during that first flight. This series of technical difficulties greatly reduced in quality and quantity the scientific material acquired during the night. Nevertheless, it was possible in the last observing hour to obtain a number of tracings of the infrared spectrum of Mars which in combination with the recent observations from the ground in other wavelength regions have already contributed to our knowledge about the chemical composition of the Martian atmosphere.

At the end of the night, when the observational work had been concluded, one more hair-raising complication occurred. The descent of the balloon was initiated by a radio command which opened the helium valve at the top of the balloon. After the valve had opened and enough helium had escaped to give the balloon the appropriate moderate descent rate, another command was given to close the helium valve to avoid any further acceleration. This command failed and in spite of a variety of experiments the helium valve could not be

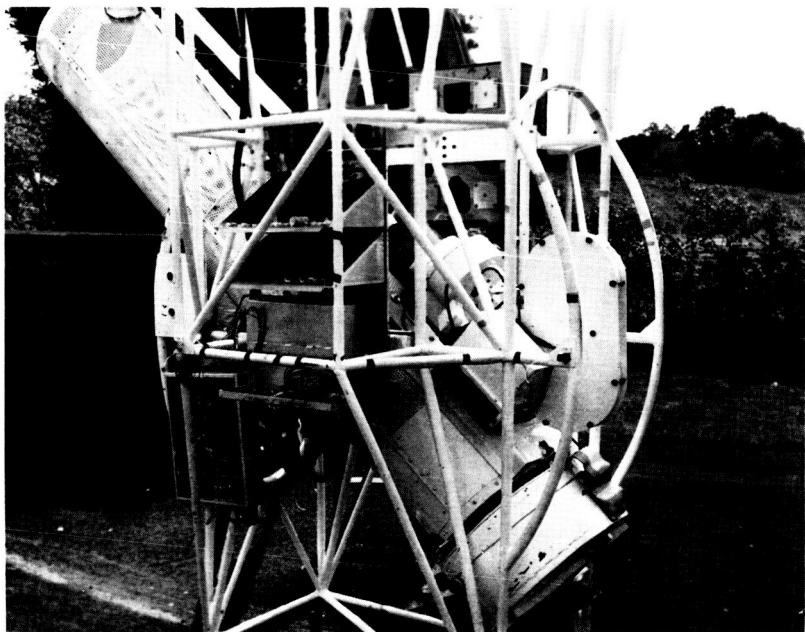
persuaded to close again. In consequence the balloon with the telescope descended more and more rapidly. Finally it became necessary to cut (by another radio command) the balloon from the parachutes and let the telescope come down to earth on the parachutes which are always carried as a safety device. This type of landing is very much rougher than direct landing by balloon. Nevertheless, by miraculous luck the damage suffered by the whole instrument at landing was quite modest and its repair less than a tenth of the total cost of the instrument.

It is obviously always a bit of a disappointment when a first flight of a new instrument does not right away provide all the new exciting scientific data of which theoretically it is capable. But this dims little the pleasure that the new data, however limited, have given us, and much increases our eagerness to correct the inadequacies of the instrument and to get it ready for its next flight.

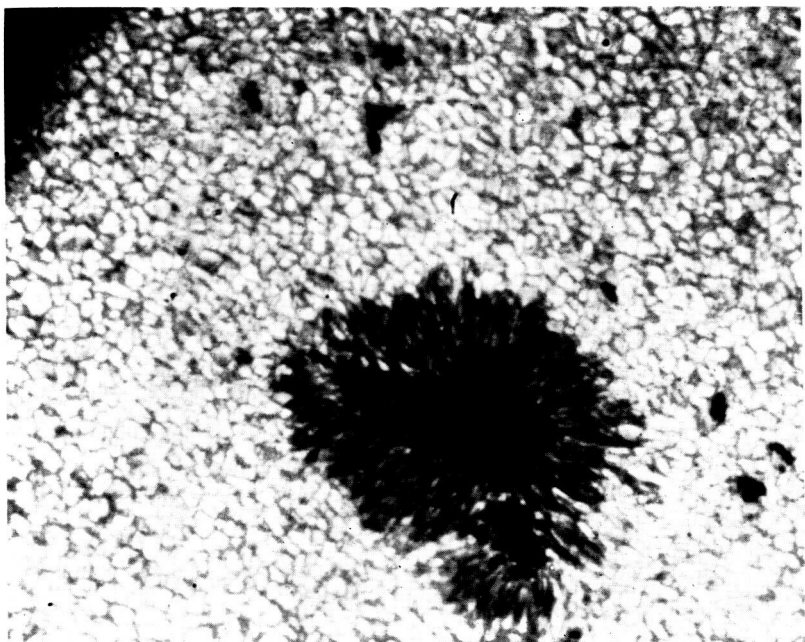
I have sketched the story of Project Stratoscope up to its present status. May I once more emphasize that Project Stratoscope is only a small facet of the total space activity in this country. But even this small facet clearly requires funds beyond the means of an individual university. Project Stratoscope has been sponsored by three Government agencies, Office of Naval Research, National Science Foundation, and National Aeronautics and Space Administration. These three agencies have in Project Stratoscope a remarkable record not only in continuous effective cooperation with each other but also in their persistence of giving us astronomers in Princeton the freedom to make the scientific and technical decisions.

Even with this strong financial and moral support from the Government, however, we astronomers in Princeton would still be incapable of carrying out the Stratoscope experiments if it were not for the existence of daring engineers and the commercial firms to which they belong who are ready to cast their lot for a good while into a risky pioneering undertaking like Project Stratoscope. We astronomers may know the scientific problems which need attacking and may understand what basic type of instrumentation is needed, but it is the ingenious engineers who—in close and continuous contact with us—design, build, and operate the entire equipment and thus make this type of experiment possible.

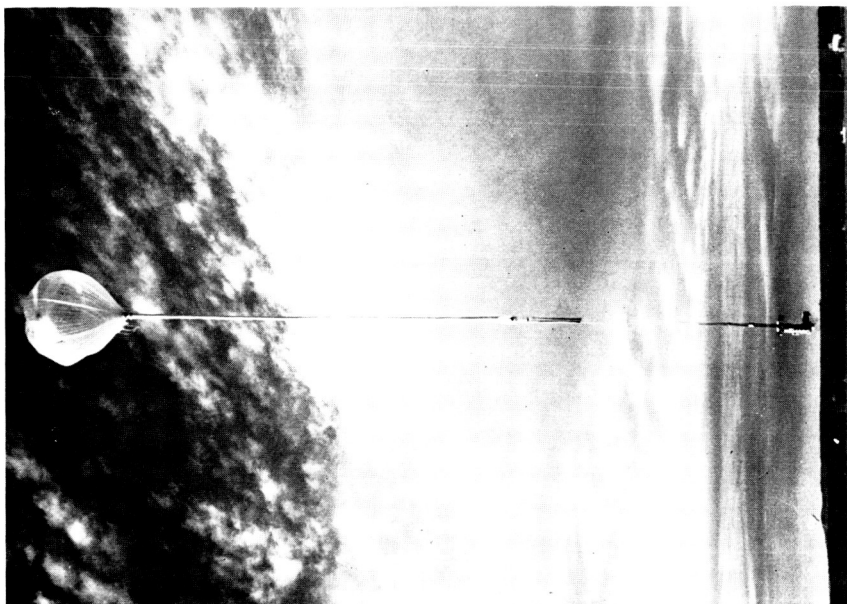
Of all the factors, however, which have to be favorable to make an undertaking like Project Stratoscope possible, historically the most remarkable seems to me the spirit prevalent at this time in this country that gives us with enthusiasm the opportunity to proceed with an endeavor that basically has an abstract scientific character and aim. For an astronomer it is an incredibly wonderful time and place to be alive.



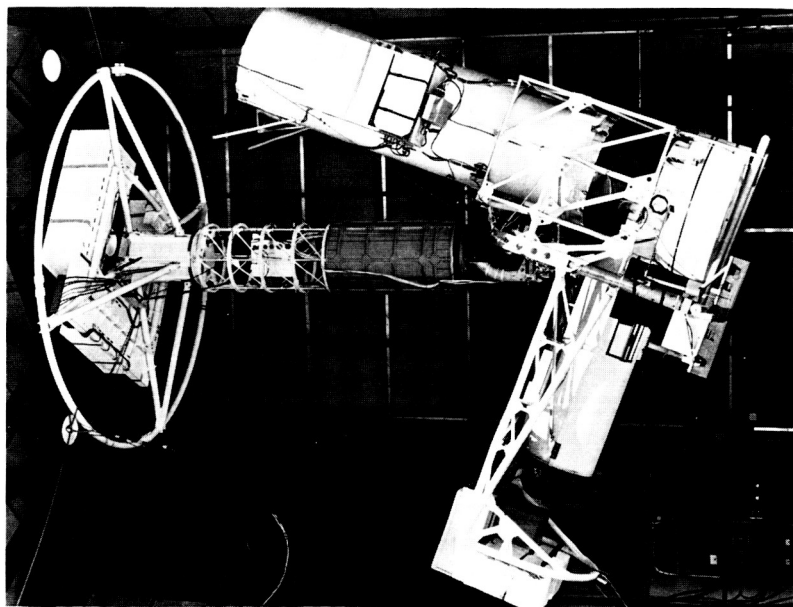
1. Stratoscope I. The cylindrical cell at the bottom of the main tube contains the 12-inch primary mirror. The flat elliptical container is the 35-mm. film magazine. Beside it, the rectangular box houses the TV camera which transmits the same picture just being photographed down to the ground station.



2. Section of the solar surface photographed with Stratoscope I. The penumbra of the sunspot consists of nothing but narrow long filaments. The sunspot is surrounded by the granulation which covers the entire solar surface; the bright patches of the granulation are hot convective gas masses rising from the interior.



2. Stratoscope II seconds after its first launch. On top is the "launch balloon" which contains all the necessary helium. During ascent the helium will expand and fill the "main balloon" (here still stretched into a thin cylinder) until it forms a sphere 240 feet in diameter. The telescope at the bottom is attached to the main balloon via a suspension containing the antennae for the radio links and two parachutes.



1. Stratoscope II suspended in its test housing. The tipped L-structure contains the telescope proper, with the 36-inch primary mirror in the bottom of the main tube and the spectrometer at the left end of the side arm.